Abstract

Many physics analyses using the Compact Muon Solenoid (CMS) detector at the LHC require accurate, high resolution electron and photon energy measurements. Following the excellent performance achieved in Run I at center-of-mass energies of 7 and 8 TeV, the CMS electromagnetic calorimeter (ECAL) is operating at the LHC with proton-proton collisions at 13 TeV center-of-mass energy. The instantaneous luminosity delivered by the LHC during Run II has achieved unprecedented values, using 25 ns bunch spacing. High pileup levels necessitate a retuning of the ECAL readout and trigger thresholds and reconstruction algorithms, to maintain the best possible performance in these more challenging conditions. The energy response of the detector must be precisely calibrated and monitored to achieve and maintain the excellent performance obtained in Run I in terms of energy scale and resolution. A dedicated calibration of each detector channel is performed with physics events exploiting electrons from W and Z boson decays, photons from π0/η decays, and from the azimuthally symmetric energy distribution of minimum bias events. This note presents the Preshower run II calibration plots and the refined calibration and excellent performance of the CMS ECAL that were achieved for the CMS 2018 Run II data legacy reprocessing.
CMS ECAL with 2018 data

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Examples of the invariant mass of photon pairs with one photon depositing a fraction of its energy in a crystal of the ECAL Barrel at $\eta = -0.03$ (top), and of the ECAL Endcap at $\eta = 1.83$ (bottom), in the mass range of the $\pi^0$.

A subset of the data collected in 2018 is used, corresponding to half of the total dataset. These events are collected by CMS with a dedicated trigger at a rate of 7 (2) kHz in the Barrel (Endcaps). The high trigger rate is made possible by a special clustering algorithm that saves only a minimal amount of information of the events, in particular, energy deposits in the ECAL crystals surrounding a possible $\pi^0$ candidate. For candidates in the Endcaps, the determination of the photon position in the region with $1.7 < |\eta| < 2.55$ is improved by the presence of the Preshower, which results in a better mass resolution.

These events are used as prompt feedback to monitor the effectiveness of the laser monitoring calibration and to inter-calibrate the energy of ECAL crystals. The $\pi^0$ mass is shown before the crystal inter-calibration.
Pi0 peaks in 2018
Z stability with time

Time stability of the di-electron invariant mass distribution for the 2018 data taking period using $Z \rightarrow ee$ electrons.

The plot shows the time stability of the median di-electron invariant mass with a refined re-calibration performed in 2019 for the full 2018 dataset. Both electrons are required to be in the ECAL Barrel (left) or in the ECAL Endcaps (right). Each time bin has around 10,000 events. The error bar on the points denotes the statistical uncertainty on the median, which is evaluated as the central 95% interval of medians obtained from 200 "bootstrap" re-samplings. The right panel shows the distribution of the medians.

At the analysis level, residual drifts in the energy scale with time are corrected for in approximately 18-hour intervals corresponding to at most one LHC fill.
Z stability with time

![Graph showing Z stability with time](image)

*CMS Preliminary 2018

59.74 fb⁻¹ (13 TeV)*

- **ECAL Barrel**
  - Median $m_{\text{ee}}$:
    - Mean: 90.1 (GeV)
    - StdDev: 0.2

- **ECAL Endcaps ($|\eta|<2.5$)**
  - Median $m_{\text{ee}}$:
    - Mean: 90.0 (GeV)
    - StdDev: 0.5

*Preliminary 2018 CMS (13 TeV) 59.74 fb⁻¹ (13 TeV)*
Z stability with time

Stability of the shower shape of the electromagnetic deposits in the ECAL for leading electrons from Z decays.

The plot shows the time stability of the shower shape of the leading electron from Z decays with a refined re-calibration performed in 2019. The event selection requires two electrons to be in the ECAL Barrel (left) or in the ECAL Endcaps (right). Each time bin has around 10,000 events. The error bar on the points denotes the statistical uncertainty on the median, which is evaluated as the central 95% interval of medians obtained from 200 "bootstrap" re-samplings. The right panel shows the distribution of the medians. The shower shape is measured by the variable $R_9$, defined as the ratio of the energy deposit in the 3x3 crystal matrix around the seed crystal to that in the supercluster. $R_9$ is responsive to changes in pedestal and noise.
Z stability with time

- **ECAL Barrel**
  - Mean: 0.951
  - StdDev: 0.002

- **ECAL Endcaps (|η|<2.5)**
  - Mean: 0.954
  - StdDev: 0.002

**CMS Preliminary 2018**

- **59.74 fb⁻¹ (13 TeV)**
Calibration effect on Z

Di-electron invariant mass distribution for the 2018 data taking period using $Z \rightarrow ee$ electrons.

The plot shows the di-electron invariant mass distribution for Z decay events with two calibration sets for the full 2018 dataset: the “preliminary” autumn 2018 calibration (RED) and a “refined” re-calibration performed in 2019 (GREEN). While for the refined calibration a complete re-calibration of the crystals was performed, for the preliminary calibration only time-dependent effects for the first part of the dataset were accounted for.

Both electrons are required to be in the ECAL Barrel (left) or in the ECAL Endcaps (right). The relative resolutions are quoted in the legend, defined as the ratio of $\sigma$ (Gaussian standard deviation of the Gaussian that is convoluted with a Breit-Wigner as the signal model (Voigtian fit)) to $\mu$ (mean). Events used in the calibration are excluded from the fit.
Calibration effect on Z
Di-electron invariant mass distribution for the 2018 data taking period using $Z\rightarrow ee$ low-bremsstrahlung electrons.

The plot shows the di-electron invariant mass distribution for $Z$ decay events with two calibration sets for the full 2018 dataset: the “preliminary” autumn 2018 calibration (RED) and a “refined” re-calibration performed in 2019 (GREEN). While for the refined calibration a complete re-calibration of the crystals was performed, for the preliminary calibration only time-dependent effects for the first part of the dataset were accounted for. Both electrons are required to be in the ECAL Barrel (left) or in the ECAL Endcaps (right) and to have low bremsstrahlung. The relative resolutions are quoted in the legend, defined as the ratio of $\sigma$ (Gaussian standard deviation of the Gaussian that is convoluted with a Breit-Wigner as the signal model (Voigtian fit)) to $\mu$ (mean). Events used in the calibration are excluded from the fit. Refined calibration fitted resolution values (1.4% and 2.7% for EB and EE, respectively) are consistent with those obtained in the final SuperCluster unfolded resolution results ($\sim 2%/\sqrt{2}$) and $\sim 4%/\sqrt{2}$ for EB and EE, respectively.)
Calibration effect on Z

**CMS Preliminary 2018**

59.74 fb⁻¹ (13 TeV)

- **Preliminary** (σ/µ=1.4%)
- **Refined** (σ/µ=1.4%)
- **ECAL Barrel**
- **Low Bremsstrahlung**

- **Preliminary** (σ/µ=3.4%)
- **Refined** (σ/µ=2.7%)
- **ECAL Endcaps** (η<2.5)
- **Low Bremsstrahlung**

**a.u.**

**m_{ee} (GeV)**
Calibration effects on Z

Di-electron invariant mass distribution for the 2018 data taking period using $Z\rightarrow ee$ high-bremsstrahlung electrons.

The plot shows the di-electron invariant mass distribution for Z decay events with two calibration sets for the full 2018 dataset: the “preliminary” autumn 2018 calibration (RED) and a “refined” re-calibration performed in 2019 (GREEN). While for the refined calibration a complete re-calibration of the crystals was performed, for the preliminary calibration only time-dependent effects for the first part of the dataset were accounted for. Both electrons are required to be in the ECAL Barrel (left) or in the ECAL Endcaps (right) and to have high bremsstrahlung. The relative resolutions are quoted in the legend, defined as the ratio of $\sigma$ (Gaussian standard deviation of the Gaussian that is convoluted with a Breit-Wigner as the signal model (Voigtian fit)) to $\mu$ (mean). Events used in the calibration are excluded from the fit.
Calibration effect on Z

\begin{align*}
\text{CMS Preliminary 2018} & \quad 59.74 \text{ fb}^{-1} (13 \text{ TeV}) \\
\text{Preliminary (}\sigma/\mu=2.3\%) & \quad \text{ECAL Barrel} \\
\text{Refined (}\sigma/\mu=2.2\%) & \quad \text{High Bremsstrahlung} \\
\text{CMS Preliminary 2018} & \quad 59.74 \text{ fb}^{-1} (13 \text{ TeV}) \\
\text{Preliminary (}\sigma/\mu=3.5\%) & \quad \text{ECAL Endcaps (}\eta<2.5\%) \\
\text{Refined (}\sigma/\mu=3.5\%) & \quad \text{High Bremsstrahlung}
\end{align*}
Performance for energy resolution

ECAL energy resolution with Zee in 2018 data

Relative electron (ECAL) energy resolution unfolded in bins of pseudo-rapidity $\eta$ for the ECAL Barrel and the ECAL Endcaps. Electrons from $Z \rightarrow ee$ decays are used. The resolution is shown separately for low bremsstrahlung electrons and for all electrons (“inclusive”). The resolution is measured on 2018 data. The relative resolution $\sigma_E/E$ is extracted from an unbinned likelihood fit to $Z \rightarrow ee$ events, using a Voigtian (Breit-Wigner convoluted with Gaussian) as the signal model.

Conclusions:
• The resolution is affected by the amount of material in front of the ECAL and is degraded in the vicinity of the eta cracks between ECAL modules (indicated by the vertical lines in the plot)
• The last point of the preliminary calibration is out of the y-axis scale of the plot
• The resolution improves significantly after a refined calibration using the full 2018 dataset with respect to a preliminary calibration for which only time dependent effects in the first part of the dataset were corrected for
Performance for energy resolution

\[
\frac{\sigma_E}{E} = \begin{cases} 
0 & \text{Inclusive} \\
0.01 & \text{Low Bremsstrahlung}
\end{cases}
\]

CMS Preliminary 2018

58.8 fb\(^{-1}\) (13 TeV)

Inclusive

Preliminary data

Refined data

Low Bremsstrahlung

Preliminary data

Refined data
Residual mis-calibration of the ECAL channel inter-calibration, as a function of pseudo-rapidity with the dataset recorded during 2018. The red, blue, and green points represent the residual mis-calibration of the intercalibration constants (IC) obtained with three different methods, and the black points represent the residual mis-calibration of the combination of the three methods. The red points refer to the IC obtained with electrons from $Z \rightarrow ee$ decays using the known $Z$ mass as energy reference. The blue points refer to IC obtained with electrons from $W$ and $Z$ decays using the tracker momentum as energy reference. The green points refer to IC obtained using photons from $\pi^0 \rightarrow \gamma\gamma$ decays. Such decays are used only for $|\eta|<2$ due to the low signal over noise ratio otherwise. The IC combination is performed by weighting the different methods relatively to energy resolution performance as measured in $Z \rightarrow ee$ decays. Between $2<|\eta|<2.5$, the $E/p$ point used for combination is out of the y-axis scale of the plot. No combination is performed for $|\eta|>2.5$, where only $Z \rightarrow ee$ decays are used.
Inter-calibration precision

CMS Preliminary 2018

58.8 fb\(^{-1}\) (13 TeV)

ECAL

- \(\sigma_{IC} \pi^0\)
- \(\sigma_{IC} E/p\)
- \(\sigma_{IC} Zee\)
- \(\sigma_{IC}\) combination

Crystal \(|\eta|\)
ES overview

The two planes of the Preshower (ES), coupled with the EE crystals, form a sampling calorimeter. The ES essentially counts the number of charged particles passing through the layers of silicon, which is an estimate of the amount of energy deposited in the ES lead absorbers. We use charged particles with momentum nearly close to minimum ionizing to calibrate the ES, so for simplicity we refer to them as “MIPs”. They are collected with the Preshower operated in high-gain mode. The design-goal accuracy of the channel-by-channel calibration is set to 5%. This corresponds to a contribution of about 0.25% to the overall EE+ES energy resolution for high-energy electrons since only a few percent of electron/photon energy is deposited in ES. The sources of response variation (sensor-to-sensor and channel-to-channel) are the sensor thickness seen by the incident particles (depends on angle of incidence), gain of the front-end electronics chain, and charge collection efficiency which varies with the radiation damage.
The plot shows the decreasing of MIP response with regard to the 2015 calibration (from 2015B to the end of 2018D) in 5 eta regions (the interval in eta is 0.2) of the front plane. The x-coordinate of each data point represents the integrated luminosity at which the MIP calibration was done. The calibration was performed every 10-20 fb\(^{-1}\).

The decreasing rate on ES+ is similar to one on ES-, thus the averages of those rates are used.

In general, the MIP responses decrease as a function of luminosity. The only exception is in the beginning of 2017 data taking, when the bias voltage was increased by 80 Volts.

The MIP response decreases faster in the higher eta region. This result implies that the ES sensors in high eta regions are more affected by the radiation damage.
MIP response decreases as a function of luminosity (Front plane)
MIP response decreases as a function of luminosity (Rear plane)

The plot shows the decreasing of MIP response with regard to the 2015 calibration (from 2015B to the end of 2018D) in 5 eta regions (the interval in eta is 0.2) of the rear plane. The x-coordinate of each data point represents the integrated luminosity at which the MIP calibration was done. The calibration was performed every 10-20 fb⁻¹.

The decreasing rate on ES+ is similar to one on ES-, thus the averages of those rates are used. In general, the MIP responses decrease as a function of luminosity. The only exception is in the beginning of 2017 data taking, when the bias voltage was increased by 80 Volts.

The MIP response decreases faster in the higher eta region. This result implies that the ES sensors in high eta regions are more affected by the radiation damage.
MIP response decreases as a function of luminosity (Rear plane)
Due to radiation damage, the Preshower response decreases with time. A data/MC correction on the runs between 2 successive calibrations to stabilize the recorded energy is applied. The correction was computed by minimizing the $\chi^2$ value between the energy distribution of data and MC.

The plot shows the calibrated deposited energy of electrons measured with the Preshower planes at low gain as a function of integrated luminosity before (BLACK) and after (BLUE) applying the correction factor. It also displays the comparison to the MC prediction (RED).

Four different data/MC correction factors are applied in this plot. They are calculated for sub-periods in a period between two consecutive high gain calibrations of an integrated luminosity of 9.7 fb$^{-1}$. The 4 sub-periods are separated with vertical lines (GREEN).

The High gain calibration, normalized to low gain by a factor of 1/6, is applied to the data points in black. Then for each sub-period, a data/MC correction factor is derived and applied at the middle of the interval, generating a slight over correction in the beginning of the intervals.

Applying the data/MC correction to the data between two ES calibrations, improves the stability of the energy measurement.
Data – MC correction

CMS Preliminary 2018
(13 TeV)

Front & Rear Plane

Deposited electron energy (GeV)

Front Plane

Deposited electron energy (GeV)

Rear Plane

Deposited electron energy (GeV)

Integrated luminosity relative to the 4th calibration of 2018 (fb⁻¹)